Ceramic Composite Hot Gas Filter Development

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Research sponsored by the U.S. Department of Energy's Federal Energy Technology Center, under contract DE-AC21-94MC31212 with McDermott Technology Inc., P.O. Box 11165, Lynchburg, VA 24506-1165; telefax 804-522-6980.

1.0 INTRODUCTION

The focus of this paper is on the fabrication and testing of full size ceramic composite filter elements. The results of sub-scale testing performed in 1995 were used to identify a starting filter composition for full-scale filter fabrication and testing portion of the program. The work included the scale up of the filament winding process to produce 1.5 meter filter elements; filter improvement/cost reduction; and finally, the production of 50 filters for testing.

2.0 BACKGROUND INFORMATION

Despite the increasing utilization of combined cycle gas turbine plants, advanced coal based power generation systems such as PFBC and IGCC are expected to play an important role in future power generating capacity in both the domestic and international markets. A critical feature of advanced coal fired power generation systems such as pressurized fluid bed combustors (PFBC) and integrated gasification combined cycle (IGCC) is the high temperature high-pressure gas stream utilized by the gas turbine. In order to protect the gas turbine components from erosion, it is necessary to remove the ash/sorbent particulates from the turbine inlet gas stream. In first generation PFBC plants such as Tidd, hot cyclones provided a sufficiently clean gas stream for the ruggedized turbine. Second generation combined cycle plants utilize a topping combustor and high temperature gas turbines that require barrier filters to meet the turbine inlet requirements. The high temperature barrier filters are therefore considered to be one of the enabling technologies for the high efficiency cycles. Testing at various DOE and private facilities has demonstrated that the level of mechanical durability exhibited by the currently available filters may not be adequate to meet the reliability demands of large power generation systems.

3.0 FILTER DURABILITY ISSUES

Hot gas filter elements must be sufficiently rugged to withstand the mechanical abuse associated with a power plant environment. Element failures have occurred during shipping, installation, and inspection/removal. Although failures during shipping or installation would not result in plant downtime, filter elements may be damaged to the extent that even normal operating conditions could lead to failure. The filter element flange must be rigid enough to support the clamping loads required to fully compress the gasket. During normal operations, the filter elements are exposed to temperatures up to 850 °C in a combustion atmosphere containing alkali, sulfur, and water vapor. Periodic back pulsing with near ambient temperature gas results in long term thermal fatigue that may produce cracking on the inside surface of the element. As in many material applications, the nominal operating conditions present only part of the challenge. Plant upset conditions, on the other hand, typically present a serious threat to the filter element and account for the bulk of the failures. For example, transition from startup burners to coal firing or coal feed problems may result in the carryover of unburned coal to the filter system and subsequent ignition on the surface of the filter element. Recent filter element failures at the PSDF were attributed to this type of operational upset that produced severe thermal gradients and associated stresses. In monolithic materials, the combination of a high elastic modulus and high coefficient of thermal expansion often results in excessive thermal stresses that produce catastrophic failure of the filter element. In some pilot scale screening tests, the thermal fatigue associated with accelerated back pulsing and the more severe thermal transients relating to turbine trips and combustor trips are simulated. Additional tests would be needed to simulate the more severe upsets associated with load changes or start up.

4.0 PROGRAM OBJECTIVES

The objectives of this program are to develop toughened ceramic hot gas filters and evaluate these filters for application in PFBC and IGCC power generation systems.

5.0 APPROACH

The essential requirements of a composite material designed to meet the program objective for a toughened hot gas filter include the following:

- stable continuous fiber
- engineered fiber coating (if required)
- rigid porous matrix
- cost effectiveness
- appropriate filtration properties

In the McDermott Technology Inc. (MTI) hot gas filter, structural reinforcement is provided by the continuous ceramic fibers while the discontinuous fibers perform the filtration function and form the rigid porous matrix of the filter element. The pure alumina Nextel™ 610 fiber was supplied as 400 filament tows with a unit weight of 1500 denier. The Saffil™ discontinuous fiber (95-97% alumina, 3-5% silica) was supplied as bulk fiber and exhibited a mean diameter of 3.5 microns. A modified filament winding process, shown in Figure 1, was developed to simultaneously deposit both continuous and discontinuous fibers on a mandrel. An En-Tec computer controlled filament winder was used for all samples. The continuous fiber was wound onto a mandrel while a dilute slurry of discontinuous fiber was pumped onto the mandrel. The excess water from the slurry was removed by the system to deposit the discontinuous fiber. The resulting preform exhibits a controlled distribution of the Nextel continuous fiber and Saffil discontinuous fiber through the wall thickness. The relative distribution of the continuous and discontinuous fibers was controlled to optimize the cost and/or performance of the filter element. Figure 2 shows the ratio of Nextel 610 to Saffil as a function of the number of layers or closures from the inside diameter to the outside diameter of the filter element. This demonstrates how the Nextel 610 was concentrated in regions of high stress near the filter element ID and OD and decreased near the center of the filter element wall. Figure 3 illustrates the typical microstructure of the MTI filter element.

This independent control of the relative amounts of continuous and discontinuous fibers can also be varied along the element axis to form an integral flange that required only trimming to length. The flange section was initially formed oversize and machined to the appropriate size and shape. The resulting flange exhibited low strength because the continuous fibers were cut in the machining operation and were therefore not anchored to the body of the element. In the net shape flange shown in Figure 4, the continuous fibers remain intact to effectively transfer the collaring loads to the body of the element and greatly enhance the integrity of the flange section.

The fabrication process is completed by the addition of a bond component in the form of a sol or liquid chemical binder to the filter element preform followed by heat treatments to convert the sol to a stable bond phase. An ideal bond system must develop bonds at fiber to fiber contact points without plugging or filling the open or continuous porosity of the filter element. The development of a uniform distribution of the bond phase is critical to developing high strength without compromising the permeability of the filter. An oxyhydroxide of aluminum, AlOOH or boehmite was used as the bond system for the vacuum wound preform. No fiber coating is required because the boehmite sol does not react with the Nextel fiber.

6.0 FILTER ELEMENT TESTING

The most recent filter element evaluations were performed at the Foster-Wheeler facility in Karhula, Finland and at the DOE/Southern Company Services Power Systems Development Facility (PSDF) in Wilsonville, AL. Three of the Karhula elements were included in the PSDF runs TC02 and TC03. Other elements from the Karhula run were subjected to accelerated pulse cycling, and thermal transient testing in the Westinghouse high temperature, high pressure test facility in Pittsburgh, PA. A field test summary of the McDermott filter elements to date is given in Table 1. Note that there have been no failures of MTI elements in any of these test programs either during the test or from shipping or inspections.

Sample filter elements were characterized in terms of their microstructure, permeability, and mechanical properties. The permeability of test specimens was determined from the face velocity and the associated pressure drop across the specimen. Compressive C-ring tests were performed on a computer controlled mechanical test machine using calibrated load and deflection sensors.

As part of the DOE Continuous Fiber Ceramic Composite (CFCC) program with support from the Virginia's Center for Innovative Technology, Virginia Tech developed an analytical model of the vacuum formed filter structure and characterized the mechanical response of thermally fatigued and field tested elements. The mechanical testing included tube tensile, ring burst, three-point bend, and cantilever bend. The cantilever bend test was performed to assess the mechanical response of the flange section of a mounted filter element. Component testing of this type should provide useful information to both the user and the modeler.

7.0 RESULTS AND DISCUSSION

Specific composition and permeability data of the filter elements from the Karhula test of 8/97 are summarized in Figure 5. These results demonstrate the consistency of the fabrication process. The C-ring results for the Karhula elements in the as-fabricated and post-test conditions are shown in Figure 6. These samples retained approximately 87 percent of the as-fabricated C-ring strength following the 581 hour Karhula test. Furthermore, the failure behavior remained non-brittle even at considerable displacement.

The mechanical response of a mounted filter under a cantilever load is shown in Figure 7. The load was applied approximately 8 inches from the mounting collar. Figure 8 illustrates the non-catastrophic failure behavior of this sample after a total displacement of one inch.

The overall status of the project is summarized in Table 2 which compares the filter requirements to the current status of the McDermott Techology Inc. filter manufacturing process. The primary challenge will be to scale up the manufacturing process to realistic production levels at acceptable cost.

8.0 BENEFITS

This program has demonstrated a hot gas filter concept and a flexible fabrication method that resulted in an oxide-oxide composite based filter with improved strength and toughness compared to monolithic filter materials. In addition, the flexibility of the process in terms of the fiber distribution should result in improved performance and cost. Finally, the fabrication process has the potential to produce 2 meter elements or larger in order to increase the filtration area.

9.0 FUTURE ACTIVITIES

The production of 50 filter elements for testing in DOE demonstration facilities is in progress. In addition, each step of the fabrication process is being re-evaluated as part of a manufacturing scale-up study.

10.0 ACKNOWLEDGMENTS

The assistance of T. J. McMahon, FETC COR, is gratefully acknowledged. In addition, the U.S. Department of Energy Continuous Ceramic Fiber Composite program has provided valuable material development support for this project. Finally, the hot gas filter modeling and testing performed at Virginia Tech by Dr. K. Reifsnider and his students X. Huang and R. Carter under the CFCC program and the Virginia's Center for Innovative Technology provided valuable understanding of the structural response of the vacuum wound material.

Table 1. Test summary of McDermott filter elements.

Test Facility	Filter Type	# of elements	Duration (hours)
Ebensburg CFB	C1, C2, C3, C4	3 of each type	250
Westinghouse HTHP	C3	4	100
FETC Combustor	C3	3	24
Westinghouse HTHP	C4M	1	100
Karhula	C4M	6	581
Karhula/PSDF TC02/TC03	C4M	3	1800
PSDF TC02/TC03	C4M	6	1219
PSDF TC03	C4M	2	660

Table 2. Hot Gas Filter Summary

Property	Req't.	Status	Challenge
size	2.4 x 60"	2.4 x 60"	complete
shape	flanged, closed end tube	closed end tube with integral flange	complete
pressure drop @10ft/min	10	5	complete
strength	1 - 4 ksi	0.8 - 1.2 ksi	moderate
toughness	non-brittle failure	non-brittle failure with high strain tolerance	Complete
thermal shock	survive severe plant upsets	MTI filter exhibits very high thermal shock resistance	complete
corrosion resistance	3 year life	No corrosion issues identified; all oxide system expected to stable	complete
scale-up	thousands/yr	Planning	No major issues identified
cost	$500-1000	Nextel fiber cost is expected to decrease with increased fiber production	moderate

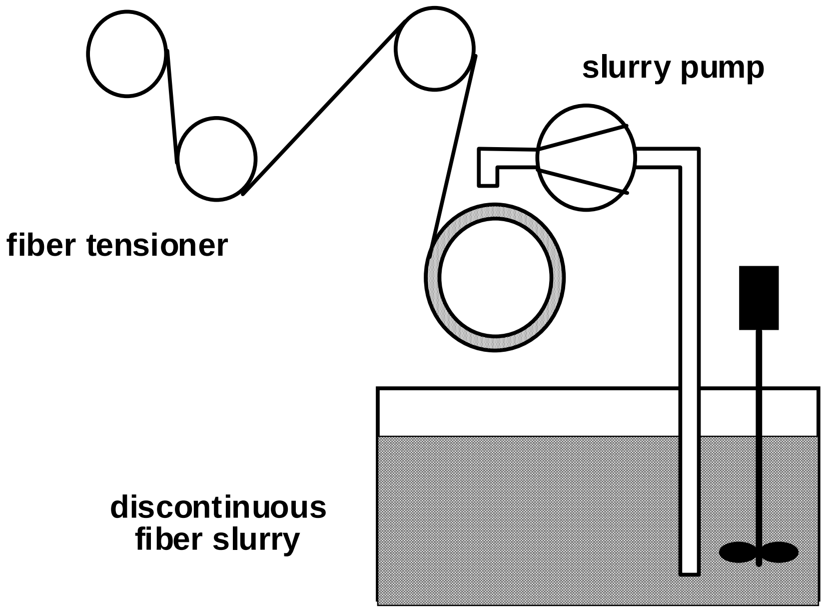


Figure 1. Schematic diagram of vacuum winding equipment.

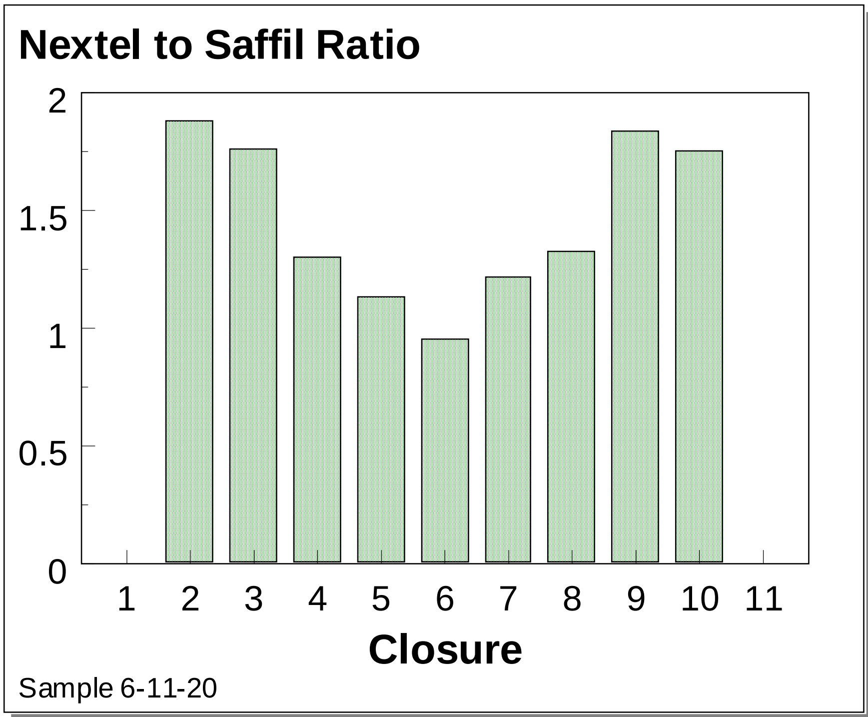


Figure 2. Example of controlled distribution of Nextel 610 and Saffil fibers.

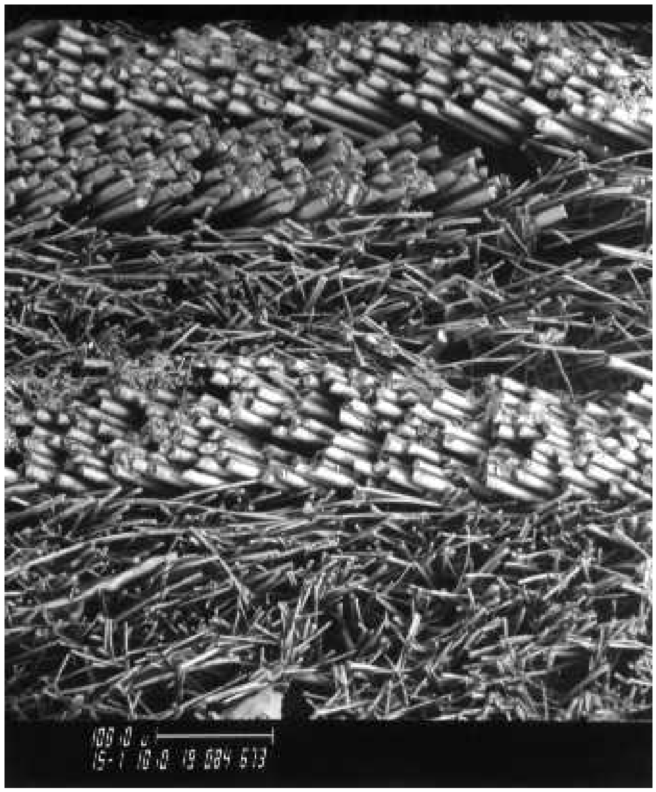


Figure 3. 150X image of filter element cross-section.

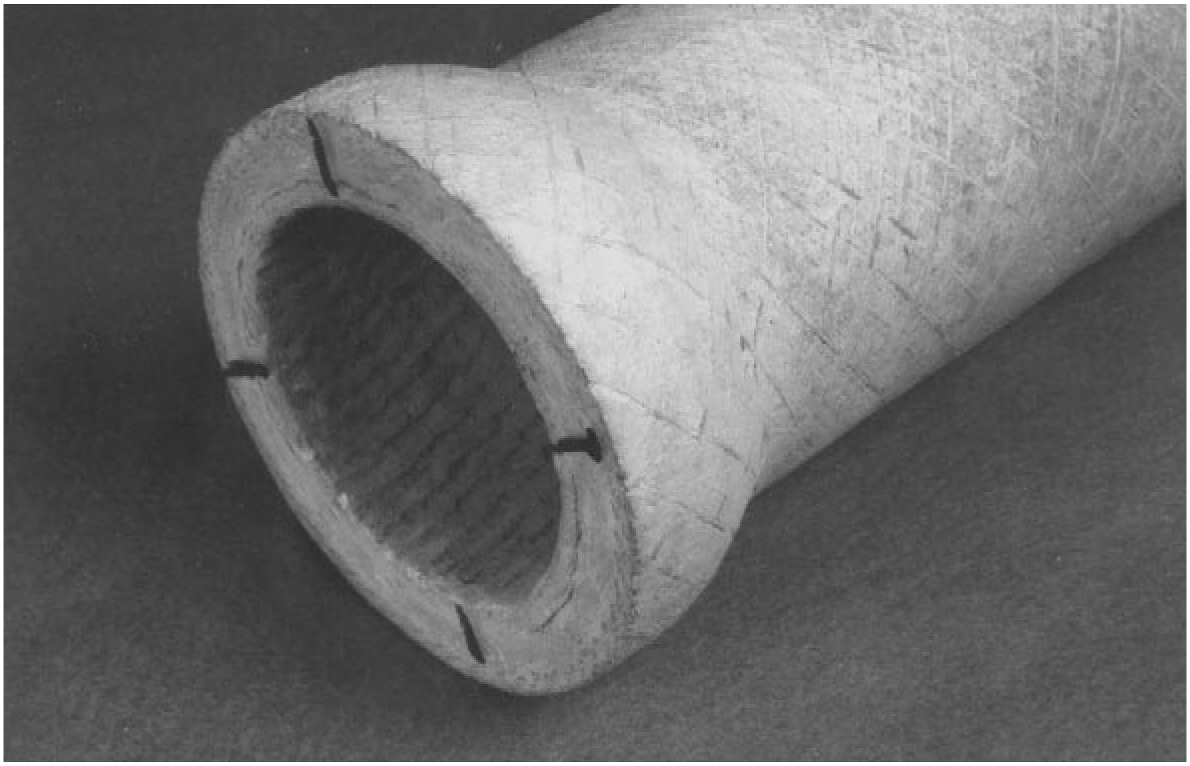


Figure 4. Photograph of net shape flange.

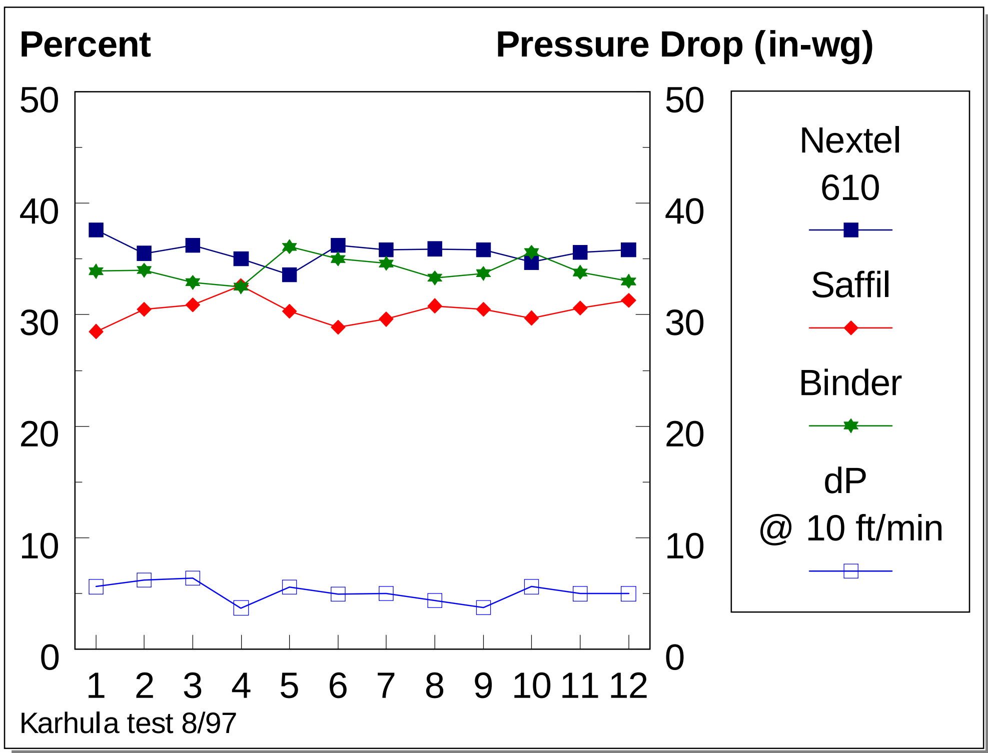
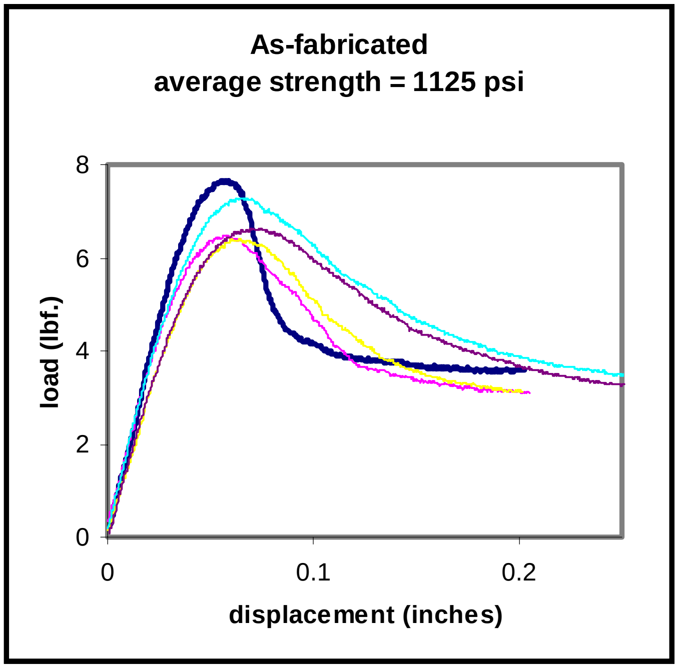


Figure 5. Composition and permeability of Karhula elements.



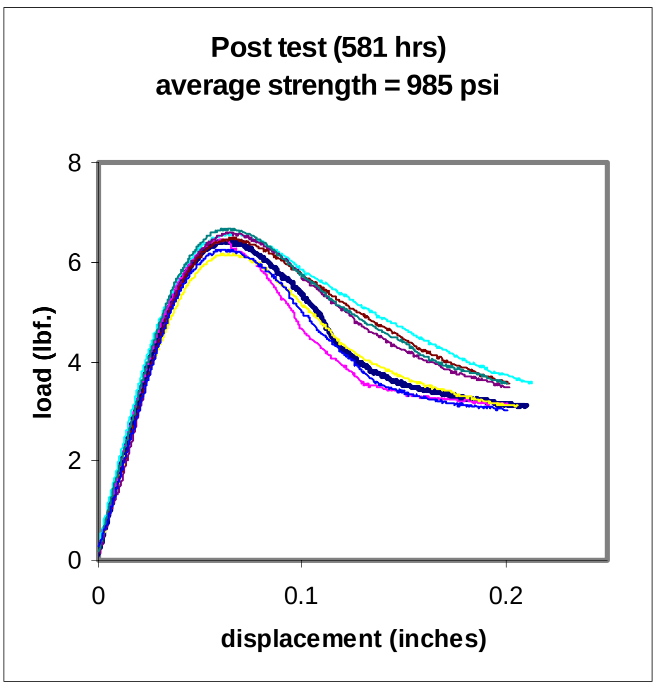


Figure 6. Load versus displacement results for as-fabricted and post-test Karhula samples.

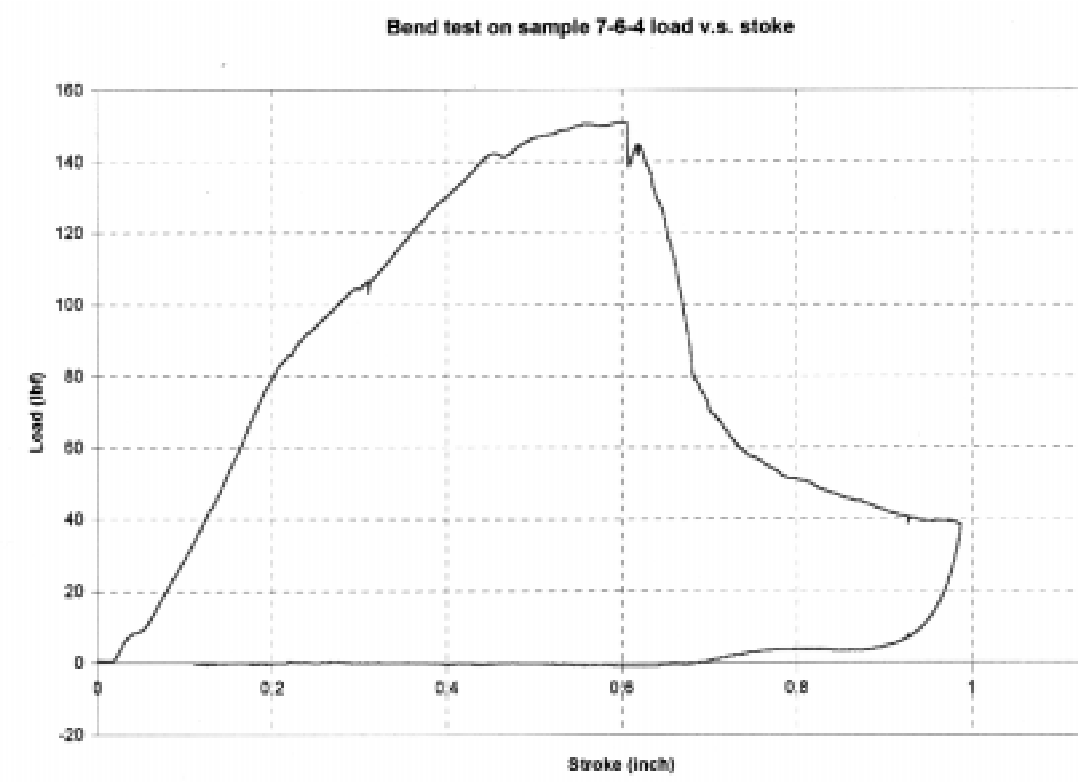


Figure 7. Load versus displacement results for cantilever flange bend test.

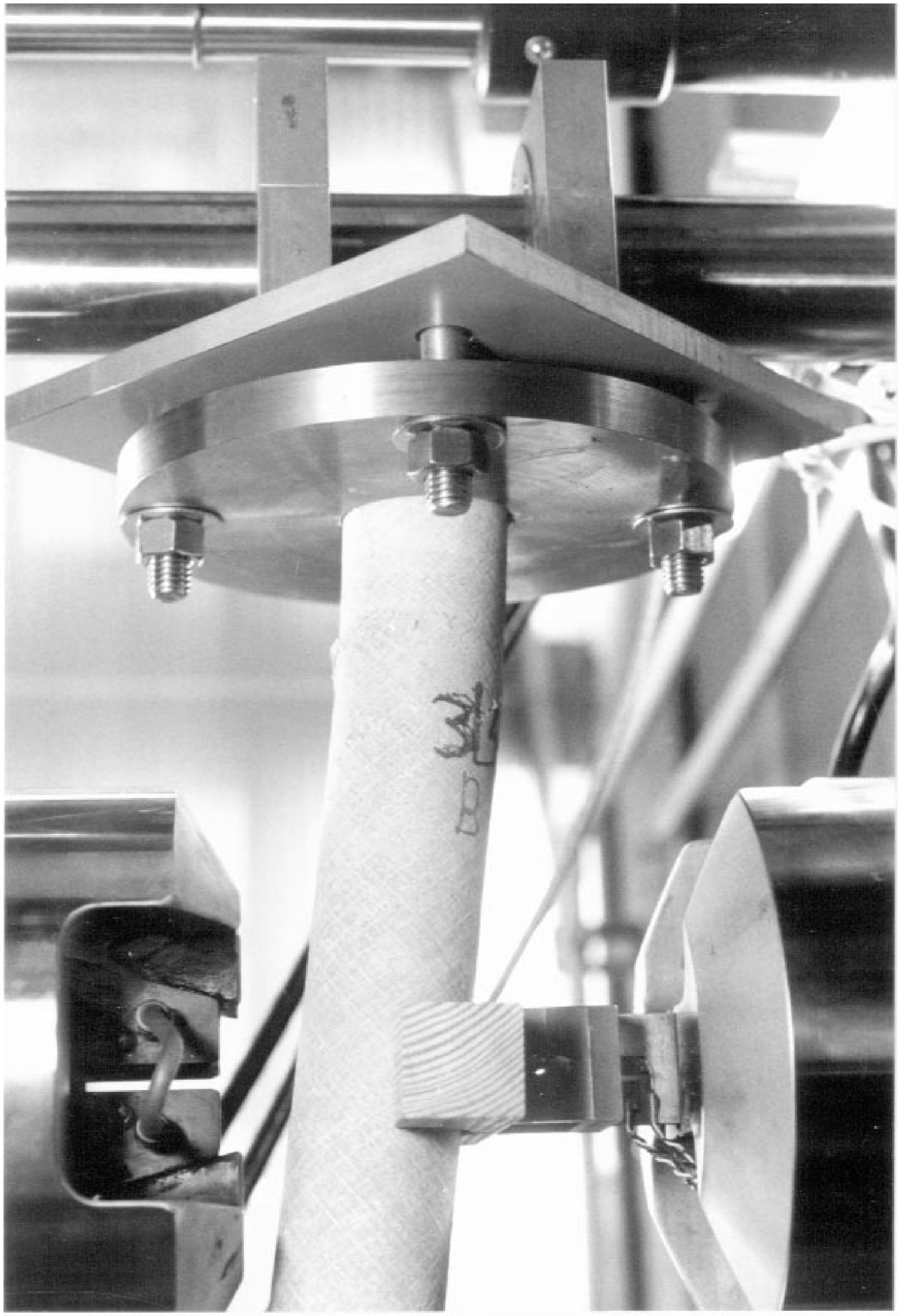


Figure 8. Photograph of cantilever flange bend test at 1 inch displacement.